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DISCUSSION OF EXPERIMENTAL INVESTIGATION OF FIRE MONITORS AND NOZZLES

(Published in October, 1951)

By G. Halbronn; Pierre Oguey, Marcel Mamin, and
François Baatard; John H. Arnold; Hunter
Rouse, J. W. Howe, and D. E. Metzler

HYDRAULICS DIVISION

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DISCUSSION

G. HALBRONN¹¹.—Current observation shows that jets emerging from circular orifices into still air do not remain cylindrical and coherent but diverge and break up into drops. This phenomenon, which is of theoretical interest, plays an important part in various technical problems, such as that of carburetor injection and that of the structure of Pelton nozzle or fire nozzle jets. The last two examples concern jets of comparable size and velocity and therefore it is advantageous to compare them so that any improvements which are likely to be made in one of these branches may be used to the benefit of the other.

Although the problem of jet diffusion has been the subject of many investigations, one cannot consider the problem as having been solved. The number of intervening factors is great—design and size of the nozzle, nature of the fluid, and head at the orifice. In addition, the factors which are likely to govern diffusion are numerous and complex—the influences of vibration, surface tension, flow turbulence, and air resistance. Moreover, research workers have not always succeeded in isolating the factors that have a major influence in the case investigated.

The first experimental research work on this subject was that of F. Savart,¹² with thin-walled orifices of 1.2-in. maximum diameter and 3.3-ft-per-sec maximum velocity. J. Plateau¹³ gave the first theoretical explanation, based on his investigations on the stability of liquid cylinders, of the effects observed by Mr. Savart, which he attributed to the action of surface tension. This process of disintegration can thus be qualified as a capillary dissolution regime.

Mr. Plateau's calculations were completed and made more accurate first by Lord Rayleigh^{14,15} and then by C. Weber.¹⁶ Roughly speaking, the length of nondisintegrated jet in this case is proportional to its velocity and to the cube root of the orifice diameter.

Some research workers, of which A. Haenlein¹⁷ was one, observed a new disintegration process when the velocity was increased. This consists in the transverse oscillation of the jet and in a very great reduction in its nondisintegrated length. According to Mr. Haenlein, this phenomenon is caused by the effect of the surrounding air. From this hypothesis, Mr. Weber endeavored to interpret Mr. Haenlein's experiments theoretically but without much success.

NOTE.—This paper by Hunter Rouse, J. W. Howe, and D. E. Metzler was published in October, 1951, as *Proceedings-Separate No. 92*. The numbering of footnotes, illustrations, and equations in this *Separate* is a continuation of the consecutive numbering used in the original paper.

¹¹ Ingénieur des Ponts et Chaussées, Détaché au titre de la Recherche Scientifique auprès des Etablissements Neyrpic à Grenoble, France.

¹² "Mémoire sur la constitution des veines liquides lancées par des orifices circulaires en mince paroi," by F. Savart, *Annales de Chimie et de Physique*, Paris, France, 1833, Vol. 53, p. 337.

¹³ "Statique expérimentale et théorique des liquides soumis aux seules forces moléculaires," by J. Plateau, Gauthier-Villars, Paris, France, 1873, p. 326.

¹⁴ "Instability of Jets," by Lord Rayleigh, from *Scientific Papers*, Vol. I, 1899, pp. 361-368.

¹⁵ "On the Instability of a Cylinder of Viscous Liquid under Capillary Forces," by Lord Rayleigh, *ibid.*, Vol. III, 1899, p. 585.

¹⁶ "Zum Zerfall eines Flüssigkeitsstrahles," by C. Weber, *Zeitschrift für Angewandte Mathematik und Mechanik*, Vol. II, No. 2, 1931, p. 136.

¹⁷ "Über den Zerfall eines Flüssigkeitsstrahles," by A. Haenlein, *Forschung auf dem Gebiete des Ingenieurwesens*, Vol II, 1931, p. 139.

G. Littaye¹⁸ then undertook further experimental studies of the phenomenon. He showed that with an absolutely circular, thin-walled orifice, having no burrs on the upstream edge, the limits given by Mr. Haenlein are easily exceeded and the capillary dissolution of the jet is maintained. Therefore, this phenomenon is not due to air action. If it were, it would occur just as well with a jet from a thin-walled orifice as with one from a thick-walled orifice or a capillary tube. However, Mr. Littaye was able to reproduce the phenomenon only with the latter two orifices, and he attributed it to the process of transformation of the parabolic distribution of the velocities in a cross section of the tube into their uniform distribution in a cross section of the jet.

When the velocity continues to increase, the transverse oscillation decreases and even disappears. However, the surface of the jet then becomes irregular on leaving the orifice and the drops formed are very much smaller than in the two former regimes.¹⁹ This latter regime, therefore can be termed the "pulverization regime." The experimental criteria of the existence of the three different regimes were given by W. Ohnesorge²⁰ in a nondimensional form. When these criteria are extrapolated, it is seen that industrial jets are practically always pulverized.

Hydraulic engineers today agree that pulverization is caused by the inner turbulence of the jet. As mentioned by the authors, tests performed in a vacuum chamber should therefore give rise in this regime, to jets having the same structure as those in air; according to present knowledge, however, such experiments have never been published. On the contrary, in the course of tests conducted at the Neyrpic Laboratory, the vacuum chamber was filled with a fine mist, which indicated an even greater disintegration of the jet and made observation impossible. This phenomenon is probably due to the sudden release of the air dissolved in the water as the jet enters the vacuum. Therefore, the experiment should be made with a liquid from which dissolved gases have been removed and would consequently be exceedingly difficult to perform. However, there is a simpler way of making sure that air action cannot be the initial cause of pulverization for, if this were the case, the phenomenon would re-occur in an identical manner with jets of the same diameter and velocity, regardless of the design of the nozzle. Now, the tests made by the authors have shown that all the devices, which were known to reduce turbulence, also cause a reduction in the diffusion of the jet. This fact alone shows that, in this case, turbulence is without doubt the initial cause of jet diffusion.

The hypotheses made by the authors to explain the mechanism of the action of this turbulence can be compared to those which were made recently in France, to account for the occurrence of "white water" in high velocity, free surface flow. It has been shown²¹ that air entrainment cannot occur upstream from a critical point at which the boundary layer, generated by the contact of the water and the face of the spillway apron, attains the same height

¹⁸ "Contribution à l'étude des jets liquides," by G. Littaye, *Publication Scientifique et Technique du Secrétariat d'État à l'Aviation*, Paris, France, 1942.

¹⁹ "The Break-up of Liquid Jets," by A. C. Merrington and E. G. Richardson, *Proceedings, Physical Soc.*, January, 1947, Vol. 59, No. 331, p. 1.

²⁰ "Die Bildung von Tropfen an Düsen und der Zerfall flüssiger Strahlen," by W. Ohnesorge, *Zeitschrift des Vereines Deutscher Ingenieure*, Vol. 81, No. 16, 1937, p. 465.

²¹ "Étude de la mise en régime des écoulements sur les ouvrages à forte pente-Application au problème de l'entraînement d'air," by G. Halbronn, Thèse de l'Université de Grenoble, France, 1951.

as the flow, and turbulent action consequently begins to make itself felt on the surface. At this point, a criterion for which the writer has endeavored to give an explicit expression must be found, such that transverse kinetic energy which the turbulence transmits to the surface droplets is sufficient to overcome the opposing stresses due, in particular, to surface tension and gravity. When this is the case, the droplets detach themselves from the body of water and entrain air as they fall back in, giving the flow its characteristic aspect.

These views are identical with those given by the authors to explain the turbulent disintegration of jets and it should be possible, therefore, to apply the same method of calculation. Unfortunately, however, even with the simplest type of nozzle, it is still difficult to evaluate the intensity of the turbulent fluctuations at the nozzle outlet and a choice between the various possible hypotheses can be made only after systematic experiments. Nevertheless, from the qualitative point of view, the effect of surface tension makes it possible to explain the experimentally verified fact that jets can remain clear and translucent (when not in the pulverized state) even when the Reynolds number in the nozzle exceeds 2,400, at which value turbulence occurs. The calculation also makes questionable the veracity of the authors' statement (under the heading, "Discussion of Test Results: Performance Tests of Recommended Monitors") that

"* * * the dependence of the turbulence upon the mean velocity tends to make the angle of diffusion independent of the velocity * * *."

This fact would doubtless be correct if the turbulence characteristics at the outlet remained the same as within the body of the nozzle, but the effect of contraction (defined as the ratio between the pipe-line diameter and the outlet diameter) is likely to change these characteristics and to invalidate the conclusion. The writer is inclined to believe that diffusion increases when the velocity of the jet increases, and it decreases, with a constant outlet cross section, when contraction increases. This confirms the statement (under the heading, "Underlying Principles of Flow: Improvement of Fire Streams") that "* * * the passages * * * should be of maximum dimensions commensurate with practicable over-all size."

This contraction effect is not shown by the experiments mentioned herein since jets flowing from the same pipe line through nozzles having different outlet diameters (and, therefore, different degrees of contraction) all have practically the same range for the same initial velocity. However, even though turbulence accounts for the diffusion on the jet in the first part of its trajectory and the occurrence of the surface protuberances which are subject to the relative wind action of the air, this latter goes on to play a predominant part in the dispersion of the jet and in the shortening of its range. This fact is clearly shown in the experiments made by A. C. Merrington and E. G. Richardson,¹⁹ in which it is seen that the diameter of the drops created does not depend on the absolute velocity of the jet but on its relative velocity in relation to the surrounding air. A thinner, and therefore more contracted, jet would undergo air action through to its center more rapidly than would a thick jet, and it is possible that this effect may counterbalance the effect of the

former's good initial performance. Some of the conclusions given here may therefore no longer be valid when use is made only of a short length of the jet, such as is the case with Pelton nozzles.

These remarks show the difficulty of the problem. The systematic study of a schematic case would be desirable but, in the more complex, practical case, only tests which are similar to those described by the authors are likely to show the constructive steps that should be taken to reduce the intensity of the turbulence, of which the occurrence is inevitable. The systematic introduction of curved guide vanes is certainly very favorable. The determination of the nozzle's optimum angle of convergence and the physical explanation of its existence are of great value. It is of interest to note that Pelton nozzle designers have also been led along different lines to adopt convergence angles of approximately 30° . It would also be useful if the action of the guide vanes upstream from the orifice, considered by the authors as being unfavorable, were studied in greater detail since they are always used in Pelton nozzles. P. Oguey^{22, 23} even reached the conclusion that an increase in the number of vanes reduces the angle of diffusion of the jet. There is thus a contradiction for which an explanation would be desirable.

PIERRE OGUEY,²⁴ MARCEL MAMIN,²⁵ AND FRANÇOIS BAATARD.²⁶—Since 1942 the writers have studied carefully all scientific publications concerning hydraulics and this paper is the first to offer an explanation of jet dispersion that seems valid. In their research, the authors studied the means of augmenting the range of fire streams by improvement of nozzles and monitors. They have demonstrated for the first time in America that jet dispersion is due to turbulence caused by the structural details preceding the jet.

The writers have undertaken a theoretical and experimental study of the high-speed water jet to clarify the hydraulic phenomenon of dispersion and, particularly, to improve the performance of Pelton turbines. To this effect a theory of jet dispersion resulting from turbulence was established on the basis of numerous observations. This theory was then largely verified by tests made with the most varied types of nozzles, functioning under very different conditions. The conclusions obtained are valid for any kind of jet, whatever liquid is used. As a matter of fact, the calculation method recommended permits a rational study of the improvements that can be effected in jet-producing units, more particularly in fire monitors.^{27, 28} This application to fire-stream engines had already been demonstrated distinctly in 1944.

²² "Etude théorique et expérimentale de la dispersion du jet dans la turbine Pelton," by P. Oguey and M. Mamin, *Bulletin Technique de la Suisse Romande*, Nos. 21 and 22, 1944, pp. 265, 277, and 281-291.

²³ "Etude théorique et expérimentale de la dispersion du jet dans la turbine Pelton," by P. Oguey, M. Mamin, and F. Baatard, *ibid.*, Nos. 4 and 5, 1951, pp. 37-47, and 53-64.

²⁴ Conseiller d'Etat, professeur à l'Ecole polytechnique de l'Université de Lausanne, Switzerland.

²⁵ Chef de travaux à l'Ecole polytechnique de l'Université de Lausanne, Switzerland.

²⁶ Chef de travaux à l'Ecole polytechnique de l'Université de Lausanne, Switzerland.

²⁷ "La dispersion du jet d'eau à grande vitesse: Part I, Etude théorique et expérimentale de la dispersion sous l'effet de la turbulence," by Pierre Oguey and Marcel Mamin, *Publication No. 16*, Polytechnic School of Lausanne University, Lausanne, Switzerland, 1944. (A theoretical and experimental study of dispersion due to the phenomenon of turbulence including general equations, laws of similitude, and applications to Pelton turbines.)

²⁸ "La dispersion du jet d'eau à grande vitesse: Part II, Nouvelle étude expérimentale," by Pierre Oguey, Marcel Mamin, and François Baatard, *Publication No. 17*, Polytechnic School of Lausanne University, Lausanne, Switzerland, 1951. (A new experimental study; transformation of small jets into drops)

Structure of a Dispersed Jet; Hypotheses and Fundamental Equations.—On leaving the nozzle, a jet undergoes—from its contracted section on—the phenomenon of dispersion. Instead of keeping its cylindrical shape as the laws of hydrodynamics would require, it reveals two distinct areas—(1) a central, convergent, homogeneous zone composed of water and (2) a divergent, heterogeneous zone, surrounding the first, and consisting of a mixture of air and water. It is this mixture (area 2) which gives the jet its dispersed appearance and, at a certain distance from the outlet, makes it look like a steam jet. It can be mathematically demonstrated (and experimentally verified) that the outer limit line of the jet and the inner limit line that separates the homogeneous zone from the heterogeneous one are symmetrical with the theoretical limit line of the cylindrical jet, with which they form an angle α .

The basic hypotheses of the theory (as applied by the writers and the authors) are as follows:

1. The air resistance is negligible.
2. The axial velocity V_1 of all the water particles is constant in intensity and direction and equal to velocity V_0 in the contracted section. Velocity V_1 is constant for a horizontal jet. In a slanting jet, V_1 diminishes with the altitude. In this connection, it must be mentioned that the Bernoulli equation is valid when it is applied to each jet particle considered as a projectile. On the contrary, the equation is not valid for the jet considered as a whole because the equation of continuity is not applicable between two sections crossed by a mixture of air and water, the density of which is unknown.

3. Furthermore, the writers maintain that at the periphery of the jet, a water particle must submit to:

(a) A centripetal action caused by atmospheric pressure and by a molecular attraction which creates a surface tension T_s and

(b) A centrifugal action from the inside, caused by the liquid turbulence characterized by the "Reynolds number for the apparatus" R . If the centrifugal forces are superior to the centripetal ones, the particle in question escapes from the jet surface at a radial speed V_2 that is constant (it is constant, at any rate, to the moment when it is distant enough to be exposed to the action of the surrounding air).

Thus the angle α , which is characteristic of the jet dispersion, is indicated by the following basic equation:

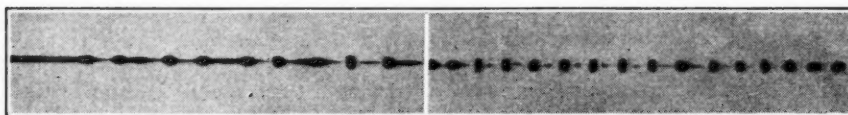
$$\tan \alpha = \frac{V_2}{V_1} = \sqrt{F(R) - \frac{2 T_s}{\rho d_o V_1^2}} \dots \dots \dots (13)$$

in which d_o is the diameter of the jet in contracted section and $\rho = \gamma/g$ is the specific mass of liquid.

Transformation of a Jet into Drops, Without Dispersion.—In Eq. 13, if the quantity under the radical is negative or equal to zero, it denotes that surface tension is prevalent and that no jet dispersion will occur. The stream will be

without dispersion including dispersion of big jets, influence of structural details preceding the jet, and applications to Pelton turbines.)

transformed into drops according to a process which is entirely visible²⁹ in Fig. 22. The liquid cylinder (which must submit to a surface tension) being unstable, forms dilated, periodical zones that are separated by a liquid cylinder with a diminishing diameter. This cylinder can free itself from the dilated zones and, after yielding to its own molecular attraction, can contract itself into a droplet which is much smaller than adjacent drops. Then the air sucks these droplets out of the track of the large drops, which explains the vapor that may be observed around big long-distance jets. Clouds were visible on the photographs of big jets, in the files of the writers and the authors alike. However, the contrary phenomenon may occur if one of the two dilating zones has more attracting power than the other. In this case, the small cylinder connects itself with the stronger zone without forming an intermediary droplet.



(a) JET VELOCITY, 15 METERS PER SECOND
(2,067 FT PER SEC)

(b) JET ENTIRELY TRANSFORMED, WITHOUT
DISPERSION

FIG. 22.—TRANSFORMATION OF A JET INTO DROPS WITHOUT DISPERSION
(CAMERA EXPOSURE ABOUT 0.000001 SEC)

Dispersion of Big Jet (Fire Stream or Jet of Pelton Turbine).—In any section where dispersion is already strong, the jet surface is very irregular. Thus, it is legitimate to admit that the effect of surface tension has become negligible and, therefore, that the phenomenon of dispersion is caused by turbulence only. The expression of $\tan \alpha$ is then reducible to

$$\tan \alpha = \sqrt{F(R)} \dots \dots \dots (14)$$

If the axial velocity V_1 is constant, the specific weight γ of the air and water mixture at a distance y from the axis will be lower than the specific weight γ_o of the water, and

$$\frac{\gamma}{\gamma_o} = f\left(\frac{y}{y_o}\right) = f\left(\frac{2y}{d_o}\right) \dots \dots \dots (15)$$

A theoretical calculation based on the foregoing three hypotheses, and the study of the appearance of the experimental curves allowed the writers to develop the general equation of this curve.

The curves of Eq. 15 are presented in Fig. 23 for successive sections of jet.³⁰ Each section is characterized by the ratio $\beta = \frac{a_{\min}}{y_o}$ in which a_{\min} is the minimum radius of the homogeneous-remaining zone. The theory, tested by experiments easy to perform, determines the distance from the outlet where

²⁹ "La dispersion du jet d'eau à grande vitesse: Part II, Nouvelle étude expérimentale," by Pierre Ogüey, Marcel Mamin, and François Baatard, *Publication No. 17*, Polytechnic School of Lausanne University, Lausanne, Switzerland, 1951, p. 65, Figs. 26 and 27.

³⁰ *Ibid.*, p. 40, Fig. 19.

these curves must be placed in order to have the complete image of any jet, whatever its diameter (d_o) and the generating net head H .

The process of dispersion is illustrated³¹ by the photographs in Fig. 24. On leaving the nozzle outlet, the jet first shows streaks, then protuberances which move away from the axis more and more, and gradually transform themselves into drops and droplets on which the surrounding air may then have a braking action. The action of the air begins only at a distance which is equal to 70 or 80 times the jet diameter at the outlet; but protuberances are not waves caused by air resistance (on many photographs it is impossible to distinguish the direction in which the stream is circulating), rather they are waves provoked by internal turbulence, which confirms the fundamental hypothesis of the theory. The observations reported by the authors fully confirm both the processes of dispersion thus described, and the effect of air resistance.

Conditions for the Similarity of Jets.—The authors have presented true propositions for the similarity of apparatus. It is easy to demonstrate that two units which are geometrically similar in all their parts will produce streams of diameters d'_o and d''_o which will have the same dispersion characteristics, under the condition that their Reynolds number is equal; that is, that

$$R' = R'' \dots \dots (16)$$

or that

$$\frac{V'_o d'_o}{\nu'} = \frac{V''_o d''_o}{\nu} \dots \dots \dots (17)$$

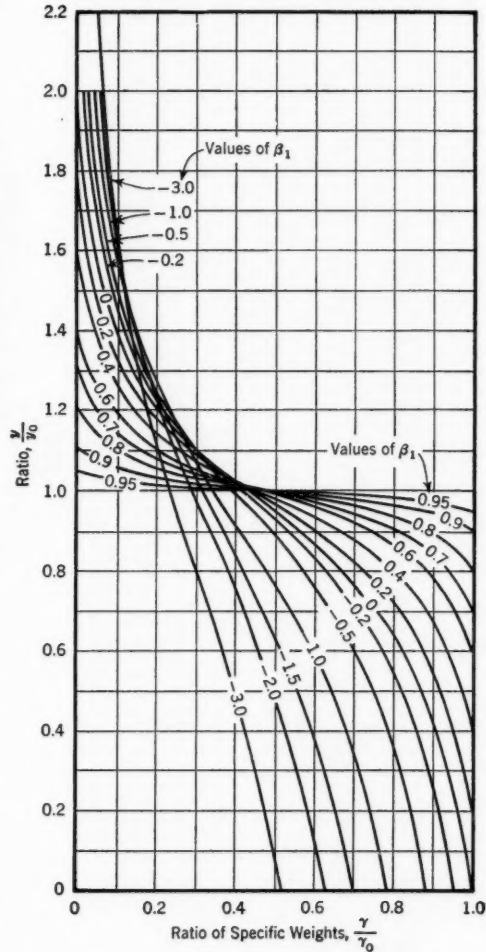
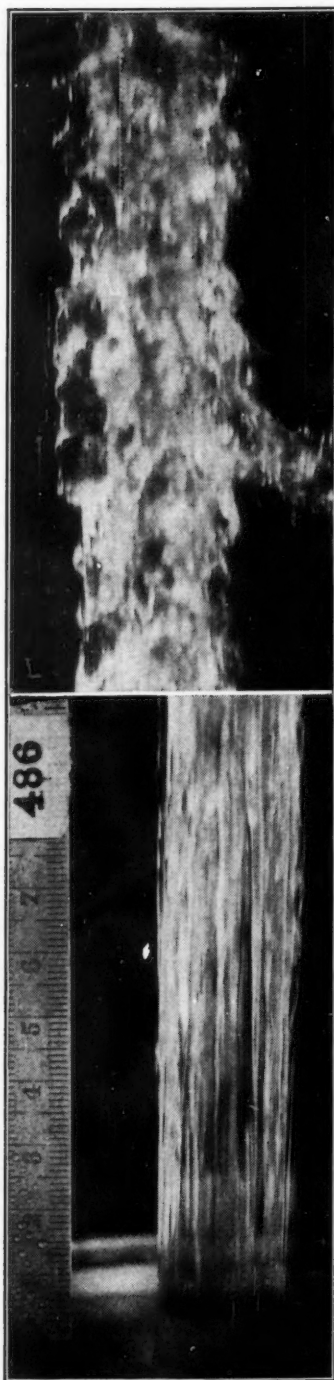
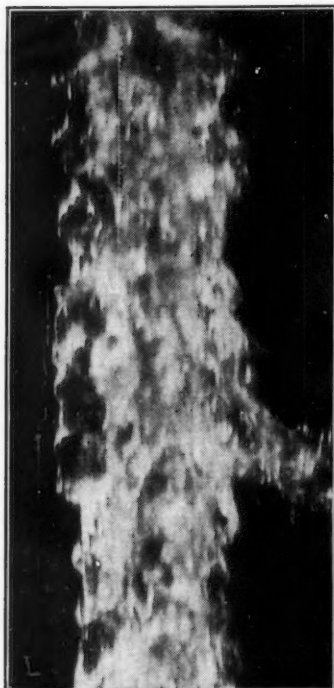


FIG. 23.—RELATION BETWEEN THE SPECIFIC WEIGHT RATIOS, $\frac{\gamma}{\gamma_o}$, OF THE AIR AND WATER MIXTURE, AND THE RADIUS RATIOS $\frac{y}{y_o}$ AT DIFFERENT SECTIONS OF A DISPERSED JET

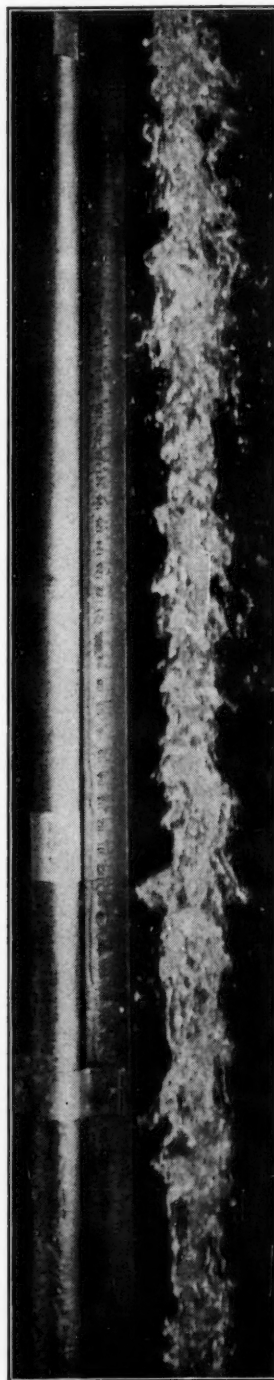
³¹ "La dispersion du jet d'eau à grande vitesse: Part II, Nouvelle étude expérimentale," by Pierre Oguey, Marcel Mamin, and François Baatard, *Publication No. 17*, Polytechnic School of Lausanne University, Lausanne, Switzerland, 1951, Figs. 31, 35, and 36.



(a) NEAR THE OUTLET ORIFICE



(b) SMALL DISTANCE FROM ORIFICE



(c) LARGE DISTANCE FROM ORIFICE (JET ENTIRELY DISPERSED)

FIG. 24.—PHOTOGRAPHS OF A JET MOVING AT A RATE OF THIRTY-SIX METERS PER SECOND (118 FT PER SEC) UNDER A HEAD OF SIXTEEN METERS (107 FT)

$\nu = \mu/\rho$ being the kinematic coefficient of viscosity and ν being the dynamic viscosity. If H is the net head (that is, the total hydraulic generating energy of the jet), Eq. 17 can also be written

$$\frac{d'_o \sqrt{H'}}{\nu'} = \frac{d''_o \sqrt{H''}}{\nu''} \dots \dots \dots (18)$$

Comparison of Different Nozzle Designs as to Dispersion of Jet.—The angle α is characteristic of the dispersion. It is possible to demonstrate that $\tan \alpha$ is a function of (construction nozzle) $d_o \sqrt[4]{H}$. The next step is to try to reduce the value of $\tan \alpha$ (measured or calculated for any one nozzle) to those which might be obtained with the same nozzle with a diameter d_{oc} under a head H_c . Since α_c is a function of (nozzle construction) $d_{oc} \sqrt[4]{H_c}$, the expression for a given nozzle is

$$\tan \alpha_c = \tan \alpha \frac{d_{oc}}{d_o} \sqrt[4]{\frac{H_c}{H}} \dots \dots \dots (19)$$

If all nozzle tests are thus reduced to the same diameter and to the same head, the values of $\tan \alpha_c$ can differ only as a result of the influence of construction differences (shape and measurements) in the tested nozzles. Eq. 19 permits an easy comparison of very different types of nozzles tested with any kind of head or discharge and it enables one to see the influence of construction on dispersion—that is, on the quality of the jet.

It is evident that dispersion is one of the factors that cause the lowering of the jet performance, but it is not the only factor. The losses in head due to friction and eddies must also be considered. For instance, by placing a honeycomb with numerous and very long walls into a nozzle, the turbulence, and consequently the dispersion, are diminished, while losses in head caused by friction increase. Therefore, it will be wise to measure the velocity in the contracted section of the jet by means of a Pitot tube and to calculate the loss of energy in the unit before and after each modification in the construction. Thus only will it be possible to determine the arrangements that yield an optimum result.

Eq. 19, which the writers have used with very good results on the nozzles of Pelton turbines, could certainly confirm the comparisons made by the Iowa Institute of Hydraulic Research on different types of fire monitors. The improvement of a unit, whatever its dimensions and functioning conditions, may then be planned by using a single model unit.

Conclusions.—The general conclusions of the writers' study, and their comments on the work reported by the authors may be summed up as follows:

1. The dispersion of a jet depends essentially on turbulence, the latter being a function of the head (total hydraulic energy before the nozzle outlet) and of the construction (dimensions and form) of the structural details that precede the outlet orifice. Air resistance has no direct effect on dispersion proper. The effect of air resistance is felt only when the droplets, which have escaped from the jet, are sufficiently distant to be braked by the air.

2. The laws of similitude, once established, permit the planning of a unit to be built from a model which is geometrically similar in all its parts and which operates under such a head that the Reynolds numbers can be equated (Eq. 16). Besides, a convenient criterion for the comparison of different units will be provided by introducing the specific values $\tan \alpha_c$ (Eq. 19).

3. The conclusions advanced by the authors afford an interesting means of confirming that method of calculation. Besides it proves obviously the care with which they have made their experimental study of jets, their sagacity in the interpretation of their observations, and the great value of their work.

JOHN H. ARNOLD²².—During 1940 and 1941 the National Board of Fire Underwriters conducted a series of experiments on the subject of this paper. The results were reported to the International Association of Fire Chiefs, in 1943, in an unpublished paper by Clarence Goldsmith, M. ASCE, entitled "The Effective Reach of Powerful Streams." The research described in the present paper is in accord with suggestions made by Mr. Goldsmith. Like the authors, Mr. Goldsmith concluded that there was a need for a redesign, and an increase in the waterway areas of the current types of monitors. Under the heading, "Introduction," the authors report an increase in the reach of streams obtained with a modified tip and a lengthened nozzle. In similar observations, Mr. Goldsmith found that the increase ranged from 2% to 30%, the latter being the maximum obtained on one test.

In the test following Eq. 5, the authors state that C_L " * * * may be considered a constant for a given conduit form, such as a fixed contraction ratio or fixed proportions of an elbow, regardless of the conduit dimensions." Possibly, this conclusion was adopted because variations may not have much practical significance. The theories of fluid turbulence seem to apply logically, and it may be a fair assumption that liquid protuberances would appear as readily in a vacuum, although no practical methods of proving this assumption seem feasible. It may well be that there is adequate proof of the introduction of serious secondary spiral currents in the sweeping curves of the bends in conventional monitors. It is on this assumption that the entire new design, proposed in the paper, is based.

In preliminary work by the National Board of Fire Underwriters, much difficulty was encountered in deciding at what point the stream ceased to be effective. The same general criteria were used as in the present paper. However, varying judgment and lack of clear visibility by day, even with the use of a transit (as in the present work), gave unsatisfactory results and led to the development of a system of night observations with lights.

The writer believes that the authors' comparisons of results showing an advantage for the proposed new types of monitors are not a true measure of the relative merits. In each instance, the waterway areas of the new types are considerably larger than those in either of the old types which were used for comparison. It would be valuable to know if there is any assurance that better results would be obtained from the new type if comparisons were made with monitors of the old design, but having equivalent waterway areas.

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The paper offers theories that may be of much value in reconsidering current practice on the subject, and it has made a start toward putting these theories into practice. However, it is felt that much further work and much more accurate comparisons of the old and the new designs are needed before any practical superiority can be proved.

HUNTER ROUSE,³³ M. ASCE, J. W. HOWE,³⁴ M. ASCE, AND D. E. METZLER³⁵.—To Messrs. Halbronn, Oguey, Mamin, Baatard, and Arnold the writers are greatly indebted for the considerable background, breadth, and practical scrutiny which their discussions have given to the original investigation. The international aspect of these contributions, moreover, supports the writers' belief as to the general importance of the subject. It is not only heartening that their findings have been verified in other countries, but also stimulating that the profession most closely concerned with fire-stream efficiency shows a healthy interest in advancement and yet a cautious insistence upon full verification of their conclusions.

Mr. Halbronn's excellent documentation of the topic more than compensates for the meagerness of the writers' bibliography. His comparison of the mechanism of jet dispersion with that of air entrainment by high-velocity flow in an open channel is extremely apt. Although there are essential differences due to the continuous generation of turbulence and the restoring force of gravity in the latter phenomenon, in both it is the disruption of the free surface by the turbulent filaments which is the basic factor.

The writers' statement (under the heading, "Discussion of Test Results: Performance Tests of Recommended Monitors") that " * * * the dependence of the turbulence upon the mean velocity tends to make the angle of diffusion independent of the velocity * * * " tacitly assumes constancy of the boundary geometry. As Mr. Halbronn correctly believes, an increase in the relative size of the approach section will decrease the angle of diffusion, provided that the accompanying reduction in flow stability is otherwise offset. The writers' statement is also a rough approximation rather than a precise generalization because of the fact that the phenomenon involves viscous and capillary effects as well as those of geometric form. Any general law, therefore, must be expressed in terms of not only a series of length ratios describing the monitor, nozzle, and jet form, but also the Reynolds and Weber numbers—and the Froude number as well, if characteristics of the relative trajectory are to be included.

Mr. Oguey and his colleagues have had the courage to undertake the first approach to such a formulation, although the result is of practical necessity somewhat less than general. To the extent that unpredictable upstream effects can be eliminated, their method of analysis is without doubt a useful one for the immediate vicinity of the nozzle. Unfortunately, it is still the monitor itself which produces the major disturbances, and the essential compactness of fire-monitor design makes the prediction as well as the elimination of these disturbances at best a difficult matter.

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The mechanism of droplet formation without dispersion surely plays a predominant role in small jets, but the writers do not believe that this is the phenomenon which gives rise to the fine mist surrounding the jets from certain types of nozzles. The source of the mist seems to lie instead in the small-scale boundary-layer turbulence near the jet surface, for it was most prominent in streams from very long nozzles and from those which had a slight break in profile near the tip. Large droplets, on the contrary, appeared to result from turbulence of larger scale generated upstream from the nozzle.

The writers are in wholehearted accord with the similarity criteria which Messrs. Oguey, Mamin, and Baatard propose—except for their belief that the Froude and Weber numbers are fully as important as the Reynolds number. The performance of Pelton nozzles and that of fire nozzles are, to be sure, judged from somewhat different points of view, but—except for range—the basic factors involved in both are just the same. The writers strongly recommend that engineers interested in either aspect of the problem refer to the two papers^{27,28} cited in the discussion—not only for the authors' extensive analysis, but also for the superb photographic evidence of the dispersive action of turbulence which they contain.

The writers must confess to a complete ignorance of the Goldsmith report³⁶ prior to the receipt of Mr. Arnold's discussion. This report contains a wealth of experimental data on the reach of streams. Contrary to the writers' findings, however, Mr. Goldsmith concluded that an increase in pressure will invariably increase the effective reach. Although the writers' method of observation may well have been less precise than that of Mr. Goldsmith, they do not believe that either inaccuracy of measurement or the admittedly arbitrary definition of effective reach could account for the distinct and systematic reversal of the curves shown in Fig. 20.

Mr. Arnold's question as to the constancy of C_L necessarily involves the hydraulics of all closed conduits rather than that of fire monitors alone. At high Reynolds numbers the coefficients of any conduit transition tend toward constant values—particularly if the transition is not well streamlined. The writers agree that the testing of fire streams in a vacuum is not practicable, especially in view of Mr. Halbronn's account of just such an attempt; nevertheless, their basic hypothesis does not appear subject to challenge on any other grounds. The generation of spiral flow by conduit bends³⁷ is hardly an "assumption" in view of the experimental evidence which is available in many related fields.

Of primary importance, in the writers' opinion, is the point raised by both Mr. Arnold and Mr. Halbronn as to the effect of enlarging the approach passage. Enlargement of cross section actually has two effects which are quite distinct. On the one hand, the reduction in mean velocity is accompanied by a reduction in the turbulence intensity. On the other hand, however, the increase in boundary spacing permits the scale of the turbulence to

³⁶ "The Effective Reach of Powerful Streams," by Clarence Goldsmith, published and distributed by the Educational Committee, International Assn. of Fire Chiefs, 1943.

³⁷ "Engineering Hydraulics," Ed. by Hunter Rouse ("Steady Flow in Pipes and Conduits," by V. L. Streeter, Chapter VI), John Wiley & Sons, Inc., New York, N. Y., 1950, pp. 419-423.

increase. Only if the same degree of stabilization is maintained by the insertion of guide vanes as the section is enlarged will the jet be appreciably improved. This was clearly demonstrated by two supplementary tests described in the paper. First, enlargement of the approach section to 2.5 ft without guide vanes actually resulted in greater jet dispersion, for the large spacing of the walls permitted the formation of equally large eddies by the crushed-rock baffle. Second, the institute monitor produced an inferior jet when inlet and outlet ends were reversed, for it was not the enlargement of passage which had increased the range of the stream but rather the proper guidance of the flow just before the barrel. From these observations it appears reasonable to conclude that a rams-horn monitor of large diameter would be better than one of small diameter only from the standpoint of internal loss in head.

With regard to Mr. Halbronn's question about the efficacy of guide vanes or a honeycomb just before the nozzle, the writers can only rephrase their previous statements. If the approaching flow is very turbulent, vanes of the proper form and spacing will assuredly result in a marked improvement of the jet. However, if the flow is already relatively free from turbulence, the insertion of vanes may well increase the rate of jet dispersion because of the additional boundary-layer and wake turbulence produced by each vane.

The writers agree with Mr. Arnold that further comparative tests are needed, if only to convince engineers beyond a doubt that modern principles of fluid motion are useful practically as well as theoretically. To the other discussers the writers are grateful for much corroborative evidence of this sort.

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